# MONOLITHIC INTEGRATION
# OF
# SEMICONDUCTOR AND SUPERCONDUCTOR COMPONENTS

DARPA/ONR Contract No. N00014-90-C-0226

Honeywell Sensor and System Development Center
10701 Lyndale Avenue South
Bloomington, MN 55420

1 April 1992 - 30 June 1992







Program Manager: Paul W. Kruse Paul W Kruse Phone #: 612/887-4441
Principal Investigator: Burgess Johnson Burgess Johnson Phone #: 612/887-4505
Section Head: David W. Nielsen D Nielsen 7/8/92 Phone #: 612/887-4576
Department: Norman A. Foss NA Foss Phone #: 612/887-6424

## 2.0 PROGRAM SUMMARY

The goal of the program is to develop transistor technology compatible with high transition temperature superconductor technology so that transistor pixel switches can be integrated with $YBa_2Cu_3O_7$ superconducting microbolometers in the same silicon substrate. A 4x4 matrix-addressable superconducting microbolometer array will be delivered at the completion of the program.

## 3.0 PROGRAM STATUS

### Task 1.0: Vendor Selection

Mary Weybright, a graduate student in electrical engineering at Stanford University working under the direction of Prof. James D. Plummer, has been engaged as a consultant to model the performance of bipolar transistors at low temperature, in order to determine doping profiles needed for the transistor switches at each pixel.

The monolithic bipolar transistors have been fabricated by Honeywell's MICRO SWITCH Division of Richardson, Texas, and donated to the contract at no cost to the contract. The transistor fabrication task has been deleted from the contract statement of work.

### Task 2.0: First Fabrication Run (completed)

#### Task 2.1: Film Development

Superconducting films of $YBa_2Cu_3O_7$ were grown in-situ on 3 - inch silicon wafers coated with amorphous silicon nitride and polycrystalline yttria stabilized zirconia (YSZ). The films were grown by ion beam sputtering. These films show onset of superconductivity at ~88 K and zero resistance at ~65 K. The temperature coefficient of resistance (TCR) was about 0.15 $K^{-1}$ at the midpoint of the transition (~73 K). The substrates used are ideal for fabrication of microstructures by silicon micromachining techniques. These films were grown using a combination of pure ozone from Honeywell's ozone distillation system, and ordinary oxygen. The growth temperature for optimum superconducting properties was between 700° C and 735° C. These growth temperatures are believed to be low enough to allow survival of the transistors which will be embedded in the substrate.

**Task 2.2:** Mask Design

The first fabrication run used existing masks from DARPA/ONR Contract #N00014-88-C-0394.

**Task 2.3:** Vendor Electronics

For the first fabrication run, transistors were not embedded in the substrate.

**Task 2.4:** Integrated Device

No working bolometers were produced in the first fabrication run. Due to inadequate passivation, the $YBa_2Cu_3O_7$ film on the bolometer structures was attacked by the KOH solution that was used to etch the silicon to thermally isolate the bolometers. In addition, the electrical contact pads did not adhere to the substrate. These problems were solved in a subsequent processing run funded by Honeywell which was completed in December, 1991.

**Task 2.5:** Device Evaluation

Room temperature resistance measurements were performed on the first two wafers of the first fabrication run.

**Task 3.0:** Second Fabrication Run

**Task 3.1:** Film Development

The superconducting properties of the $YBa_2Cu_3O_7$ films on silicon wafers coated with $Si_3N_4$ and YSZ have been improved compared with those grown under task 2.1. The oxygen pressure in the chamber has been increased and a small amount of silver is co-sputtered with the Y, Ba, and Cu in order to increase the critical current and reduce the noise in the films. Some films show onset of superconductivity at ~88 K and zero resistance at ~72 K, with a temperature coefficient of resistance (TCR) of about 0.30 $K^{-1}$ at the midpoint of the transition (~79 K). A film with this TCR on a thermally isolated microstructure could provide a bolometer with a sensitivity which is high enough for high performance imaging applications using a staring array. Other films have been grown with a transistion midpoint temperature of 83 K, but the TCR of these films at the transition midpoint is only about 0.16 $K^{-1}$. The substrates used are ideal for fabrication of microstructures by silicon micromachining techniques. The growth temperature for optimum superconducting properties (720°C to 740°C) is still believed to be low enough to allow survival of the transistors which will be embedded in the substrate.

The 1/f noise in $YBa_2Cu_3O_7$ films grown at Honeywell on silicon substrates with $Si_3N_4$/YSZ buffer layers is now low enough that if they were used in a large thermal imaging array of microbolometer pixels 50 μm x 50 μm in size, the 1/f noise voltage would be only about 4 times larger than the Johnson noise voltage, under typical operating condtions.

Noise measurements have been performed at the University of Minnesota, our subcontractor, on $DyBa_2Cu_3O_7$ films grown at the University of Minnesota on $SrTiO_3$ and $LaAlO_3$ single crystal substrates. Measurements of the peak in the excess noise spectral density at the foot of the resistive transition in these films show that for low magnetic fields (less than approximately 0.5 Tesla), the excess noise is due to vortex motion. The noise does not appear to be caused by charge trapping and detrapping at grain boundaries. For magnetic fields larger than about 0.5 Tesla, the noise properties are qualitatively different. This is thought to be due to the density of vortices becoming comparable to the density of grain boundary junctions in the samples.

**Task 3.2:** Mask Design

The masks for the transistors and microbolometers have been delivered. In the 4 x 4 arrays, each pixel (including transistor) will occupy an area 125 μm x 200 μm.

**Task 3.3:** Vendor Electronics

Honeywell's MICRO SWITCH Division has delivered the wafers with bipolar transistors that will be used in the second fabrication run to produce 4x4 arrays of microbolometers with a transistor at each pixel. These transistors were fabricated by modifying MICRO SWITCH's standard fabrication process according to suggestions by Mary Weybright, our consultant at Stanford University, in order to achieve good performance at low temperatures. Mary Weybright's suggestions were guided by previous low temperature (77 K) measurements on transistors from a pilot run using MICRO SWITCH's standard process.

**Task 3.4:** Integrated Device

Experiments have been carried out to determine the microbolometer process steps that cause significant damage to the transistors. Subjecting the transistors to 750°C in a furnace in nitrogen for 4 hours (in order to simulate the conditions of $YBa_2Cu_3O_7$ film growth) causes a reduction by about a factor of 2 in the room temperature current gain for some transistors. However, for transistors fabricated slightly differently, there was minimal damage after this heat treatment. The sputter deposition of the $Si_3N_4$ layer that provides the underside of the thermally isolated structures causes a reduction in the current gain of the transistors, but the damage is easily reversed with a rapid thermal anneal in air at 410°C for 10 seconds. Annealing in forming gas, the preferred method of repairing transistor damage caused by sputtering, is not possible because the hydrogen in the forming gas converts the $YBa_2Cu_3O_7$ film into an insulator. Other tests to determine damage to the transistors during microbolometer processing are in progress.

The microbolometer process sequence for the second fabrication run has been established, except for possible modifications to avoid processing damage to the transistors.

**Task 3.5:** Device Evaluation

Measurements of transistor performance at low temperature show a current gain of 20 at 77 K. This is believed to be an adequate current gain for operation of a large focal plane array of microbolometers with transistors at each pixel.

All 24 of the wafers delivered by Honeywell's MICRO SWITCH Division have been characterized at room temperature. The current gain and leakage current were measured.

Devices fabricated in the recent processing run funded by Honeywell have been evaluated. A responsivity of 1300 volts/watt with a dc bias current of only 1 μA was measured at a substrate temperature of 73 K in a microbolometer occupying a 125 μm x 125 μm area. In thermal imaging applications, pulsed bias currents of about 100 μA would be used, resulting in a responsivity of 130,000 volts/watt. A 12-element linear array showed responsivity nonuniformity less than 7% over most of the array. The detectivity, D*, measured at a frequency of 7 Hz, was 7.5 x$10^8$ cm $Hz^{1/2}$/Watt. The noise was dominated by 1/f noise in the Au/$YBa_2Cu_3O_7$ contacts. It is expected that this contact noise can be eliminated by straightforward process modifications, resulting in an improvement in the D* at 7 Hz by about a factor of 10. In the microbolometers that were tested, there was no significant degradation of the electrical properties of the superconductor during the processing required to fabricate the microbolometers.

**Task 4.0:** Third Fabrication Run

A request has been submitted to delete this task from the contract statement of work, due to lack of funds.

## 4.0 ACCOMPLISHMENTS (for 1 April 1992 to 30 June 1992)

**Task 1.0:** Vendor Selection

No work was performed on this task during this period.

**Task 2.0:** First Fabrication Run

No work was performed on this task during this period.

**Task 3.0:** Second Fabrication Run

**Task 3.1:** Film Development

The resistive transition of the films grown at Honeywell on amorphous $Si_3N_4$ with a polycrystalline YSZ buffer layer has been improved by introducing a small amount of water vapor to the deposition chamber during film growth. A film was grown in this way with superconducting onset temperature of 91 K, a transition midpoint temperature of 83 K and zero resistance at a temperature of 70 K.

**Task 3.2:** Mask Design

The mask design for the microbolometer fabrication was completed and the masks were delivered. In the 4 x 4 arrays, each pixel (including transistor) occupies an area 125 μm x 200 μm.

**Task 3.3:** Vendor Electronics

The monolithic bipolar transistors fabricated by Honeywell's MICRO SWITCH Division of Richardson, Texas were delivered. These transistors were donated to the contract at no cost to the contract. The transistor fabrication task has been deleted from the contract statement of work.

**Task 3.4:** Integrated Device

Experiments were carried out to determine the microbolometer process steps that cause significant damage to the transistors. Subjecting the transistors to 750°C in a furnace in nitrogen for 4 hours (in order to simulate the conditions of $YBa_2Cu_3O_7$ film growth) causes a reduction by about a factor of 2 in the room temperature current gain for some transistors. However, for transistors fabricated slightly differently, there was minimal damage after this heat treatment. The sputter deposition of the $Si_3N_4$ layer that provides the underside of the thermally isolated structures causes a reduction in the current gain of the transistors, but the damage is easily reversed with a rapid thermal anneal in air at 410°C for 10 seconds. Annealing in forming gas, the preferred method of repairing transistor damage caused by sputtering, is not possible because the hydrogen in the forming gas converts the $YBa_2Cu_3O_7$ film into an insulator. Other tests on microbolometer processing damage to the transistors are in progress.

The microbolometer process sequence for the second fabrication run was established, except for possible modifications to avoid processing damage to the transistors.

**Task 3.5:** Device Evaluation

Measurements of transistor performance at low temperature show a current gain of 20 at 77 K. This is believed to be an adequate current gain for operation of a large focal plane array of microbolometers with transistors at each pixel.

All 24 of the wafers delivered by Honeywell's MICRO SWITCH Division were characterized at room temperature. The current gain and leakage current were measured.

**Task 4.0** Third Fabrication Run

A request has been submitted to delete this task from the contract statement of work, due to lack of funds.

## 5.0 PROBLEM AREAS/ISSUES

- Performance of transistors at low temperature must be adequate for good switching performance.
- Transistors must survive the high growth temperature of the $YBa_2Cu_3O_7$ films, as well as the plasma and ion beam present during $YBa_2Cu_3O_7$ film growth.
- Transistors must survive the microbolometer processing steps, such as sputter deposition of films, ion milling, and PECVD deposition of $Si_3N_4$.
- The electrical resistance of the gold contacts to the $YBa_2Cu_3O_7$ films must be low enough that small area (~10 μm x 10 μm) contacts have a resistance low compared to the bolometer resistance. Small area contacts are necessary for high fill-factor in two-dimensional arrays of microbolometers.
- The noise generated in the gold contacts to the $YBa_2Cu_3O_7$ must be ow compared to the noise in the $YBa_2Cu_3O_7$ films.

## 6.0 CORRECTIVE ACTION

- Utilize calculations of transistor performance to optimize low temperature performance.
- Reduce the growth temperature of the $YBa_2Cu_3O_7$ films as much as possible.
- Use PtSi ohmic contacts to the transistors.

- Substitute sputtered $Si_3N_4$ passivation for the PECVD deposited $Si_3N_4$, in order to minimize damage to the transistors.

- Reduce electrical contact resistance and contact noise by depositing gold in-situ by ion beam sputtering immediately after deposition of the $YBa_2Cu_3O_7$ film. The gold film will then be photolithographically patterned into the desired contact geometry.

## 7.0 GOALS FOR THE NEXT PERIOD (1 July 1992 to 30 September 1992).

- Complete a process run to fabricate 4 x 4 arrays of microbolometers integrated with transistors.

- Evaluate the 4 x 4 arrays of microbolometers integrated with transistors.

- Write the final report.

## 8.0 PUBLICATIONS

### 8.1 Papers Published in Refereed Journals

None

### 8.2 Papers Published in Conference Proceedings

B.R. Johnson, T. Ohnstein, H. Marsh, S.B. Dunham and P.W. Kruse, "$YBa_2Cu_3O_7$ Superconducting Microbolometer Linear Arrays," to be published in SPIE Conference Proceedings volume 1685, Infrared Detectors and Focal Plane Arrays.

B.R. Johnson, C-J Han, R.E. Higashi, P.W. Kruse and R.A. Wood, "Monolithic Silicon Focal Planes with High-$T_c$ Superconductor IR Sensors," to be published in the Proceedings of the IRIS Specialty Group Meeting on Infrared Detectors, NASA Ames, August 18-21, 1992.

### 8.3 Presentations

a. Invited

B.R. Johnson, "Superconducting Microbolometer Infrared Detector Arrays on Silicon Microstructures," presented at the International Superconductor Applications Convention, San Diego, CA, January 14-16, 1991.

P. W. Kruse, "Focal Plane Arrays Based Upon Thermal Detection Mechanisms," JASON Imaging Infrared Detector Workshop, LaJolla, CA, June 29, 1992.

Paul W. Kruse, "Focal Plane Arrays Based Upon Thermal Detection Mechanisms," Defense Sciences Research Council

Workshop on Multispectral Infrared Systems, LaJolla, CA, July 14, 1992.

B.R. Johnson, T.R. Ohnstein, C-J Han, R.E. Higashi, P.W. Kruse, R.A. Wood, H.A. Marsh, and S.B. Dunham, "High $T_c$ Superconducting Microbolometer Arrays Fabricated by Silicon Micromachining," to be presented at the Applied Superconductivity Conference, Chicago, IL, August 24-28, 1992.

b. Contributed

B.R. Johnson, C-J Han, T.R. Ohnstein, B.E. Cole and P.W. Kruse, "Monolithic Integration of Semiconductor and Superconductor Components," DARPA Second Annual High Temperature Superconductors Workshop, Sheraton Tara Hotel and Resort, Danvers, MA, October 3-5, 1990.

B.R. Johnson, T.R. Ohnstein, P.W. Kruse and S.B. Dunham, "$YBa_2Cu_3O_7$ Films for Infrared Bolometers on Silicon Microstructures," DARPA Third Annual High Temperature Superconductors Workshop, Hyatt Bellevue Hotel, Bellevue, Washington, September 30 - October 2, 1991.

B.R. Johnson, P.W. Kruse, and S.B. Dunham, "$YBa_2Cu_3O_7$ Films For Infrared Bolometers on Silicon Microstructures," Materials Research Society Fall Meeting, Boston, MA, December 2-6, 1991.

P.W. Kruse, "Fundamental Limits of Infrared Detectors and Arrays," JPL Innovative Long Wavelength Detector Workshop, Pasadena, CA, April 7-9, 1992.

B.R. Johnson, T.R. Ohnstein and P.W. Kruse, "High $T_c$ Superconducting Microbolometer Linear Arrays," JPL Innovative Long Wavelength Detector Workshop, Pasadena, CA, April 7-9, 1992.

B.R. Johnson, P.W. Kruse, T.R. Ohnstein, C-J Han and R.E. Higashi, "High $T_c$ Superconductor Infrared Bolometers on Silicon Microstructures," American Ceramic Society Meeting, Minneapolis, MN, April 13-17, 1992.

B.R. Johnson, T.R. Ohnstein, H.A. Marsh, S.B. Dunham and P.W. Kruse, "$YBa_2Cu_3O_7$ Superconducting Microbolometer Linear Arrays," SPIE OE/Aerospace Sensing Meeting, Orlando, FL, April 20-24, 1992.

B.R. Johnson, C-J Han, R.E. Higashi, P.W. Kruse and R.A. Wood, "Monolithic Silicon Focal Planes with High-$T_c$ Superconductor IR Sensors," to be presented at the IRIS

Specialty Group on Infrared Detectors Meeting, NASA Ames, Moffett Field, CA, August 18-21, 1992.

B.R. Johnson, P.W. Kruse, S.B. Dunham, H.A. Marsh, C.J. Han and R.E. Higashi, "$YBa_2Cu_3O_{7-x}$ Microbolometer Arrays Fabricated by Silicon Micromachining," Materials Research Society Fall Meeting, Boston, MA, November 30-December 4, 1992.

## 9.0 FINANCIAL

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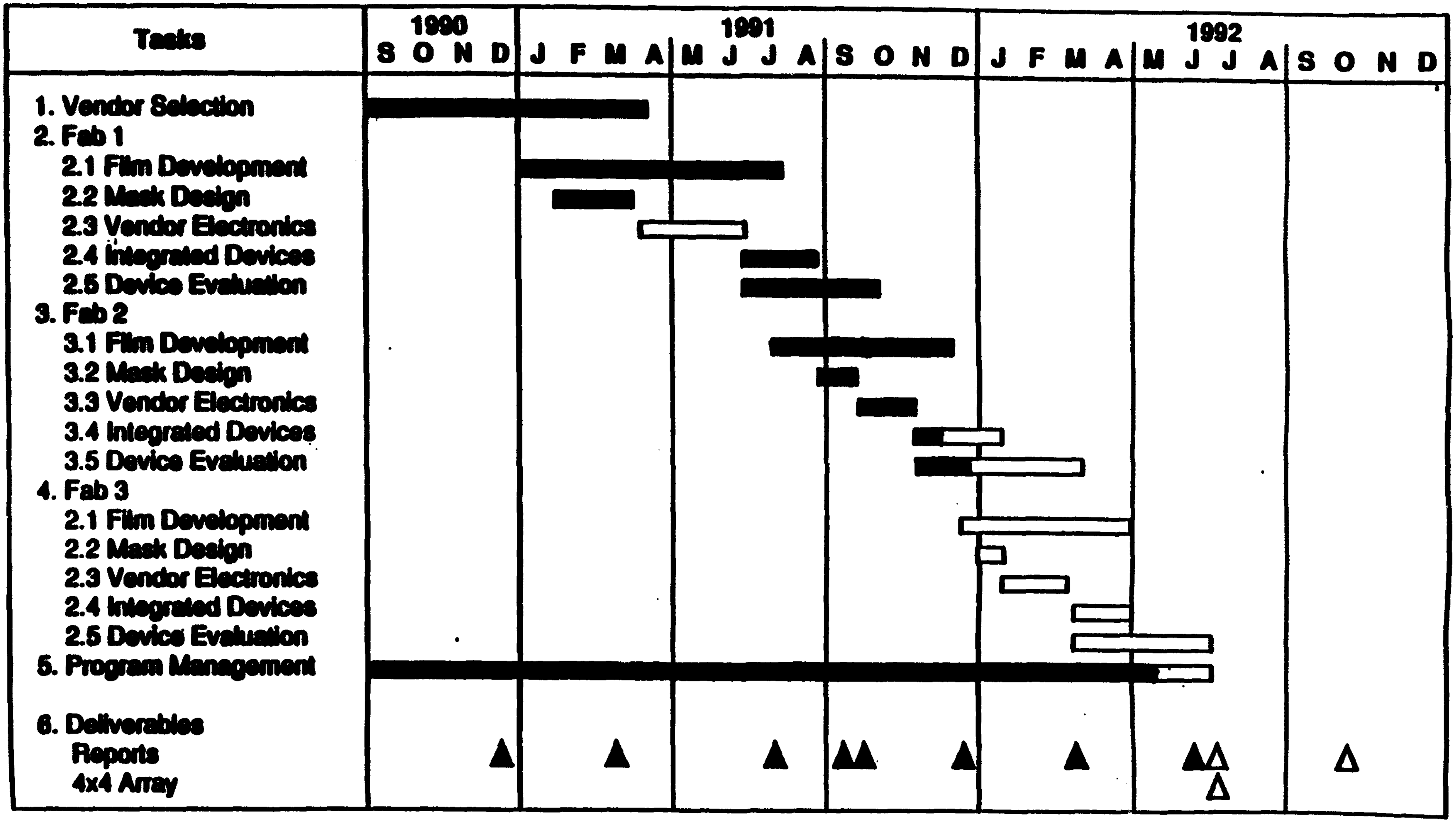
|---|---|---|
| A. | Funding Authorized | $562,022 |
| B. | Funds Expended or Committed (Week ending 30 June 1992) | $609,512 |
| C. | Additional Funds Required from ONR to Complete Contract, Assuming Third Fabrication Run Is Deleted from Statement of Work | $89,271 |

# Program Schedule

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